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## (54) ANTENNA

(71) We, PHILIPS ELECTRONIC AND ASSOCIATED INDUSTRIES LIMITED, of Abacus House, 33 Gutter Lane, London, EC2V 8AH a British Company, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:-

The invention relates to an antenna which is of generally planar form and which may have a broad instantaneous bandwidth.

Known broadband antennas include the spiral antenna and the spiral-helix or conical helix antenna. These antennas have the disadvantage of low or very low gain. An alternative broadband antenna, which is of generally planar form, is the log-periodic; this can have a useful gain, but must be rather large if it is to have a broad bandwidth.

According to a first aspect of the invention, an antenna comprises a substantially planar slot transmission line the slot of which is of generally increasing width from a narrower end to a broader end, the antenna being operable to convert electromagnetic energy within a selected range of frequencies, travelling along the slot from the narrower end, from a wave closely bound to the slot into free-space radiation, the longitudinal portion of the slot in which a substantial proportion of conversion occurs being progressively nearer to the narrower end with increasing frequency, and the maximum width of the slot being not substantially less than half a wavelength at the lowest frequencies in said range.

According to a second aspect of the invention, a travelling-wave antenna comprises a substantially planar slot transmission line the slot of which is of generally increasing width from a narrower end to a broader end, the antenna being operable to progressively convert electromagnetic energy within a selected range of frequencies, travelling along the slot from the narrower end, from a wave closely bound to the slot into free-space radiation, and the maximum width of the slot being not substantially less than half a wavelength at the lowest frequency in said range.

Where reference is made in this specification, explicitly or implicitly, to radiation of electromagnetic energy by an antenna, it will of course be understood to apply *mutatis mutandis* to reception of electromagnetic energy, since an antenna is a reciprocal device.

It should be noted that whereas the radiation in the above-mentioned spiral antenna is "broadside", i.e. a maximum in a direction approximately perpendicular to the plane of the spiral, and in the above-mentioned spiral-helix and log-periodic antennas is directed from the radiating portion of the antenna towards the feed point, the radiation of an antenna embodying the invention is a maximum approximately in the plane of the antenna and is directed away from the end of the slot to which energy is fed in operation, i.e. in the same general direction as energy travels along the slot, the antenna generally being "end-fire".

In an antenna embodying the first aspect of the invention, the slot may have longitudinally spaced pairs of mutually opposed notches at each of which pairs the width of the slot is greater than at immediately adjacent portions of the slot.

Suitably, the slot transmission line comprises a layer of conductive material on a dielectric substrate. This can provide a light, compact construction which is easy to handle and can be readily and reproducibly manufactured. The dielectric material of the substrate can assist in obtaining a broad bandwidth. The broader end of the slot is suitably at an edge of the substrate. This not only enables good use to be made of the available surface area of the substrate but can also reduce undesired interaction between dielectric and the radiated

energy.

Additional dielectric material may be provided on the substrate at the broader end of the slot. This can further increase the operating bandwidth.

The edges of the slot are suitably substantially symmetrical about a longitudinal axis of the slot. This can ensure an "end-fire" and substantially symmetrical radiation characteristic.

The width of the slot may increase at a progressively increasing rate along the slot from the narrower end. This can provide efficient radiation over a broad bandwidth. The width may vary exponentially: this can provide a relatively uniform beamwidth over a broad bandwidth.

A suitable substrate material is one consisting mainly or wholly of alumina. This is in marked contrast to known antennas formed on dielectric substrates for which alumina is generally unsuitable as it tends to prevent efficient radiation.

Embodiments of the invention will now be described, by way of example, with reference to the accompanying diagrammatic drawings, in which:-

*Figure 1* shows a first form of antenna embodying the invention;

*Figure 2* shows a second form of antenna embodying the invention;

*Figure 3* is a graph of beamwidth against normalised frequency, and

*Figure 4* shows a feeder arrangement for an antenna embodying the invention.

Referring to Figure 1, an antenna embodying the invention comprises a dielectric substrate 1 supporting on its upper major surface portions 2 and 3 of a thin conductive layer; the substrate in this case is alumina having a dielectric constant of approximately 10, and the conductive layer is gold formed by vacuum deposition. The portions 2 and 3 have opposed edges which are separated by a progressively larger gap from left to right (as drawn), thereby forming a slot transmission line of increasing width. The width of the slot at its narrower (left-hand) end may for example be 0.25 mm, and increases at a progressively increasing rate along the slot until the slot terminates at the right-hand edge of the substrate.

Microwave energy travelling along the slot from the left-hand end is initially closely bound to the slot when the width of the slot is small compared to the free-space wavelength at the relevant frequency, but as the width of the slot increases, the energy becomes less tightly coupled to the slot and progressively converted into free-space radiation. The structure thus acts as a "leaky-wave" form of travelling-wave antenna; the propagation along the slot is thought to involve changes from lower-order to higher-order Hankel function modes. The antenna provides an end-fire beam normally unobtainable with a leaky-wave form of antenna.

A cut-off frequency $f_c$ and a corresponding cut-off wave-length $\lambda_c$ of the antenna may be defined as being such that the width of the slot at its broader end is $\lambda_c/2$. The cut-off is not sharp, but at $f_c$ the broader end of the slot may be considered to act in a resonant manner, and below $f_c$ the efficiency decreases continuously with decreasing frequency in a manner analogous to a half-wavelength biconical antenna.

The resonant or standing-wave mode of operation may be extended to frequencies above $f_c$ by periodically loading the slot line in a manner somewhat analogous to a log-periodic antenna; an example is shown in Figure 2. In this case, the width of the slot increases in a generally linear fashion, but the edges of the slot are formed at regular intervals along the slot with pairs of mutually opposed notches, such as 4, the depths of the notches of each pair being approximately proportional to the width of the slot in that pair. Using such an arrangement, it was found that a forward beam could be produced with a gain of about 6 dBI; the maximum bandwidth appeared to be limited to about 3:1 owing, it is believed, to interaction between radiated waves and portions of the slot at which its width was harmonically related to the free-space wavelength at the relevant frequency.

In antennas of the forms of both Figure 1 and Figure 2, the longitudinal portion of the slot in which there is a substantial proportion of conversion of electromagnetic energy from a wave closely bound to the slot into free-space radiation is progressively nearer to the narrower end with increasing frequency within the operating bandwidth. However, whereas in the embodiment of Figure 2, conversion tends to be limited to a fairly small longitudinal portion, at least for frequencies at which the width of the slot at the pairs of notches is half the free-space wavelength, conversion occurs progressively along the slot in the embodiment of Figure 1: a substantial proportion of conversion is thought to occur in the region where the width of the slot approaches half the free-space wavelength, and a short distance beyond that width.

Large bandwidths are more readily obtainable with embodiments of the form shown in Figure 1. The provision of additional dielectric material at the broader end of the slot, as indicated by dashed lines in Figure 1, has enabled bandwidths greater than 6:1 to be obtained; sheets of a ceramic-type material with a dielectric constant of about 8 and a

thickness of about 1 mm have for example been used on both major surfaces of an alumina substrate 0.25 mm thick. It is thought that the additional dielectric material assists in approximately equalising the phase velocities in the slot line and in the surrounding medium at frequencies at the upper end of the operating range.

The beam shape of an antenna embodying the invention is determined by the length of slot required to effect a major proportion of conversion, and is thus dependent on the rate of increase of width of the slot, or in general terms the shape of the edges of the slot. The theoretical ideal of a beamwidth that is independent of frequency is satisfied by a shape that can be specified in terms of a dimensionless normalised wavelength unit. A suitable such shape for the edges is provided by a pair of exponential curves of the form

$$y = \pm A \exp (p x)$$

where $y$ is the half-width of the slot and $x$ is the distance along the slot from an arbitary zero; the factor $p$ determines the beamwidth. To put into effect the theory which would require curves extending to infinity, it is noted that when $x$ is large and positive, the great majority of electromagnetic energy travelling along the slot line from the narrower end will have been converted into radiation, and when $x$ is large and negative, the energy will be tightly coupled to the line and radiation will be very small. Thus the curves may be truncated, the maximum positive value of $x$ being related to the lowest operating frequency and the maximum negative value of $x$ being related to the highest operating frequency.

A particular constructed embodiment of this kind had a slot with edges defined by the curves

$$Y = \pm 0.125 \exp (0.052 X)$$

where $X$ and $Y$ are dimensions referred to an origin at the narrower end of the slot and are expressed in millimetres; the slot transmission line was formed on an alumina substrate of width 95 mm and thickness 0.25 mm; the edges of the slot terminated at the upper and lower ends of the right-hand edge of the substrate, and the length of the slot was 115 mm. Figure 3 is a graph of the H-plane beamwidth $\theta°$ between $-3$ dB points against the dimensionless variable $f/f_c$ for this embodiment, in which $f_c$ was about 1.5 GHz. The beamwidth in the E-plane (the plane of the substrate) was substantially the same as in the H-plane, except at the lower end of the operating frequency range as denoted by a dashed line in Figure 3. A fairly uniform beamwidth was obtained over a range of about 4-18 GHz; the gain was about 10 dBI. Detailed measurements at 8 GHz showed a 3 dB beamwidth of 45°, a 10 dB beamwidth of 68°, and sidelobes in the region of $-10$ dB to $-12$ dB. In this embodiment, no additional dielectric material was used at the broader end of the slot; by using such additional material in an otherwise similar embodiment, the operating range could be extended to beyond 40 GHz.

As indicated above, the beamwidth of embodiments using slots formed by exponential curves can be varied by varying the factor $p$ in the exponential expression. It has been found that the beamwidth may in practice be limited to a range of about 30-90°; the upper limit is set by the difficulty of maintaining the characteristic radiation pattern with a short slot of rapidly increasing width, and the lower limit by mechanical considerations with a long slot of only slowly increasing width.

Curves other than exponential may be used for the edges of the slot. By way of example, two embodiments have been constructed with edges respectively defined by the equations:-

$$Y' = 48 - 6.3168 \ln (1 + 25.53 X')$$

and

$$Y' = 48 - 9.0425 \cosh^{-1} (1 + 1.1765 X').$$

In these cases, the origin has been transferred to the broader end of the slot, with $X'$ increasing towards the narrower end; dimensions are again in millimetres. The slots were symmetrical about their longitudinal axes. Both embodiments were found to radiate over a broad frequency range but to have greater variation in beamwidth than embodiments with exponential slots.

If the edges of the slot are not substantially symmetrical about a longitudinal axis of the slot, the main lobe of the antenna will of course become asymmetrical both in its shape and its disposition relative to the axis and these characteristics will tend to vary with frequency.

The invention is of course not limited to a slot line comprising gold on an alumina substrate. A conductive layer on a dielectric substrate is however a convenient form of construction: it is generally easy to form the desired shape of slot, and the substrate offers a convenient manner of providing the dielectric material which has been found to enable a

fairly broad operating frequency range to be obtained. Embodiments have been constructed with a copper clad substrate consisting mainly of alumina which is embedded in a plastics material and having a dielectric constant similar to that of alumina itself. Substrates of lower dielectric constant may be used, but this may restrict the bandwidth obtainable without additional dielectric material and may cause difficulty in making a very narrow slot to have a suitable impedance for feeding the antenna.

One form of feeder arrangement for an antenna embodying the invention is shown by way of example in Figure 4. It comprises a slot transmission line 5 which is of uniform width equal to that of the antenna slot line at its narrower end and which is connected thereto at its right-hand end (as drawn); its left-hand end terminates in an open-circuit 6. The slot line is coupled to a microstrip line, the ground plane of which is formed by the conductive layer on the upper major surface of the substrate and the strip conductor 7 of which is formed on the lower major surface of the substrate. The strip conductor crosses the slot line and is connected at one end to the ground plane by a conductive connection 8 extending through the substrate adjacent the open-circuit of the slot line. The other end of the microstrip line is connected to a miniature coaxial connector 9 at an edge of the substrate.

Other forms of feeder arrangement may be used according to requirements. The antenna slot line may for example be coupled to a microwave circuit formed on the same substrate and comprising a detector diode so as to form a broadband receiver.

The impedances of various constructed embodiments have been found to be substantially constant with frequency. With a particular feeder arrangement for a 50 ohms source, the VSWR of an embodiment was found to be better than 1.5 over its whole operating bandwidth.

An antenna embodying the invention may be used as a feeder for other forms of antenna, e.g. a parabolic reflector.

WHAT WE CLAIM IS:-

1. An antenna comprising a substantially planar slot transmission line the slot of which is of generally increasing width from a narrower end to a broader end, the antenna being operable to convert electromagnetic energy within a selected range of frequencies; travelling along the slot from the narrower end, from a wave closely bound to the slot into free-space radiation, the longitudinal portion of the slot in which a substantial proportion of conversion occurs being progressively nearer to the narrower end with increasing frequency, and the maximum width of the slot being not substantially less than half a wavelength at the lowest frequency in said range.

2. A travelling-wave antenna comprising a substantially planar slot transmission line the slot of which is of generally increasing width from a narrower end to a broader end, the antenna being operable to progressively convert electromagnetic energy within a selected range of frequencies, travelling along the slot from the narrower end, from a wave closely bound to the slot into free-space radiation, and the maximum width of the slot being not substantially less than half a wavelength at the lowest frequency in said range.

3. An antenna as claimed in Claim 1 wherein the slot has longitudinally spaced pairs of mutually opposed notches at each of which pairs the width of the slot is greater than at immediately adjacent portions of the slot.

4. An antenna as claimed in any preceding Claim wherein the slot transmission line comprises a layer of conductive material on a dielectric substrate.

5. An antenna as claimed in Claim 4 wherein the broader end of the slot is at an edge of the substrate.

6. An antenna as claimed in Claim 4 or 5 comprising additional dielectric material on the substrate at the broader end of the slot.

7. An antenna as claimed in any preceding Claim wherein the edges of the slot are substantially symmetrical about a longitudinal axis of the slot.

8. An antenna as claimed in Claim 2 or in any Claim appendant to Claim 2 wherein the width of the slot increases at a progressively increasing rate along the slot from the narrower end.

9. An antenna as claimed in Claim 8 wherein the width of the slot varies exponentially along the slot.

10. An antenna as claimed in Claim 4 or in any Claim appendant to Claim 4 wherein the substrate consists mainly or wholly of alumina.

11. An antenna substantially as herein described with reference to Figure 1 or 2 of the accompanying drawings.

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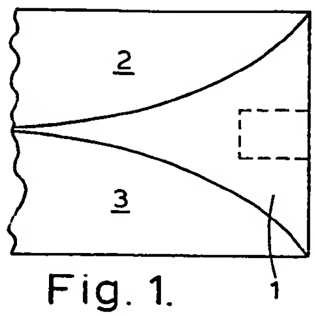


Fig. 1.

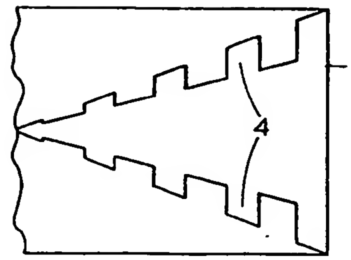


Fig. 2.

Fig. 3.

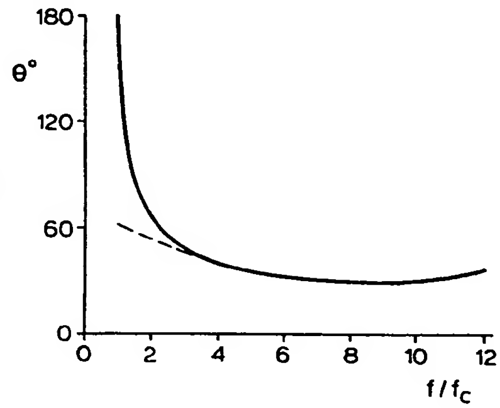


Fig. 4.